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Excitation and Multiple Dissociation of ^{16}O, ^{14}N and ^{12}C Projectiles at 32.5 MeV per Nucleon.

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ABSTRACT

The cross sections for the multiple breakup of ^{16}O, ^{14}N and ^{12}C projectiles scattered by a Au target were measured with an array of 34 detectors. The excitation spectrum of the primary projectile-like nucleus was reconstructed from the measured positions and kinetic energies of the individual fragments. Calculations of the yields based on a sequence of binary decays are presented.

The study of the breakup of a projectile into its component fragments generally has been based either on the inclusive detection of a single fragment or on two-particle coincidence measurements [1]. These types of experiments can reveal much about the breakup process when the two-body exit channels are dominant [2-3]. However, when a larger number of projectile fragments is produced in a nuclear reaction, exclusive measurements are necessary to determine the extent of multiple dissociation. Such information is important in understanding the dynamics responsible for projectile excitation in a peripheral collision, and for addressing the question of prompt versus sequential decay [4-6]. In this Letter we report exclusive measurements of the breakup of light projectiles into as many as five charged particles. Because we are able to detect beam velocity fragments with high efficiency, it is possible, under the assumption that these fragments come from the decay of the projectile, to reconstruct the excitation energy spectrum of the primary projectile-like nucleus. We find that calculations of the sequential decay of projectiles having that spectrum of excitation energy show a general agreement for the majority of the yield and reproduce the trends of the different channels over several orders of magnitude. However, they underestimate the yields for weakly populated channels and the intensity of protons at forward angles.

Beams of fully-stripped ^{16}O, ^{14}N, and ^{12}C ions were produced in the LBL Electron Cyclotron Resonance ion source and accelerated by the 88" Cyclotron to an energy of 32.5 MeV/nucleon. The target was a 2 mg/cm^2 thick gold foil. The charged reaction products were detected by a 34-element plastic scintillator phoswich array [7] centered about the beam axis in a 5x7 (horizontal x vertical) configuration with the center left open. Each detector was a truncated pyramid and consisted of a 1 mm thick ΔE element with a decay time of 2 ns followed by a 105 mm thick element with a long decay time (225ns). The detectors closest to the beam could observe particles at

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angles as small as 2.5°. The array was close-packed for maximum efficiency, with each detector subtending an angle of 5°. Particles were identified by the conventional method of short-gate and long-gate integration of the analog signal. Protons, deuterons, and particles with atomic numbers up to Z=8 were resolved. In addition, three position sensitive vertical strips of plastic scintillator [8] were placed on each side of the array to extend the angular coverage out to 35°. All coincidences between three or more particles were recorded, while those involving only two particles were scaled down by a factor of 128. Random coincidences were negligible.

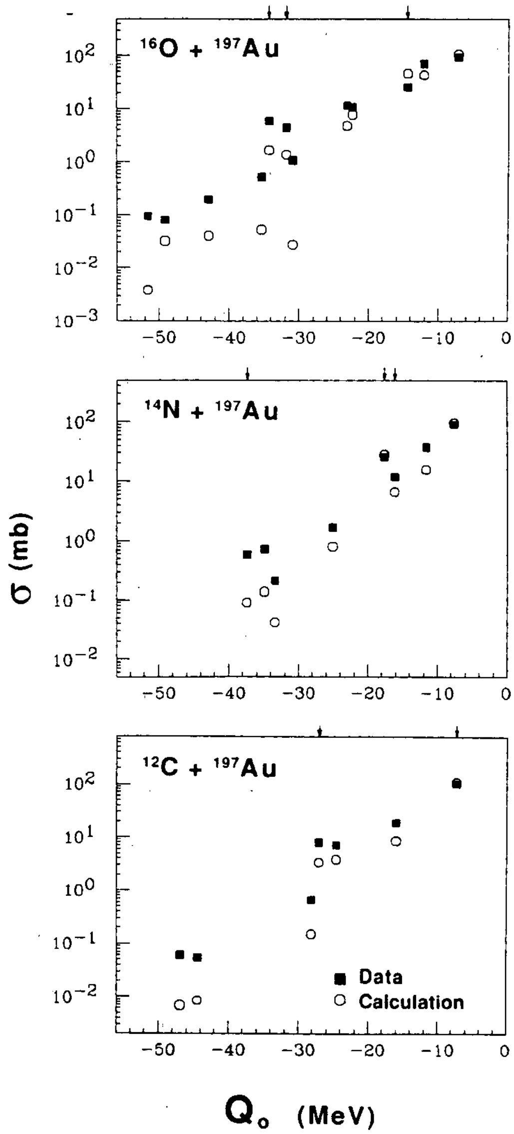
Events resulting from the breakup of the primary projectile-like nucleus were selected in the subsequent analysis by requiring that the sum of the identified charges be equal to the charge of the projectile. This, and the energy threshold for particle identification given by the 1 mm thick fast plastic, effectively eliminated any contributions of low energy particles evaporated by an excited target-like nucleus. The peripheral nature of the reaction was verified by observing that the velocities of all the detected fragments were characteristic of projectile breakup and that the relative yields of different channels were approximately independent of the target. The latter feature was demonstrated by making additional measurements on targets of ^{12}C and ^{9}Be [9].

The efficiency of the array for detecting a given breakup channel was determined empirically in the following way. The probability of detecting a particular particle in a given channel was estimated by extrapolating the observed angular distribution for that particle into the regions not covered by the array. In this way, alpha particles were found to have essentially similar angular distributions for all channels. Thus, the angular distribution of alpha particles in the C+He channel was the same as in the He+He+He+He channel. This suggests that the correlations among the particles in a given channel can be neglected in determining the efficiency of the array and that the efficiency is approximated by the product of the probabilities for detecting individually each of the fragments making up that channel. In this way the overall detection efficiencies, e.g., for the two-body channel C+He and the four-body channel Li+He+He+H, were estimated to be 67% and 32%, respectively. This procedure was checked for the two-body channels by comparing the number of light particles observed in the vertical strips with the expectation based on the extrapolation of the angular distributions measured with the array. The use of empirical efficiencies, instead of the theoretical efficiencies discussed below, reduces the dependence of the deduced cross sections on the choice of a model for the reaction.

Efficiencies were also determined theoretically by simulating the sequential decay of an equilibrated projectile with the Monte Carlo code LILITA [10]. This study showed that the effects of correlations were small and that double hits (two particles hitting the same detector element), with the exception of alpha particles generated by the decay of ^{8}Be(g.s.), could be neglected. The empirical efficiencies were well reproduced for those channels in which all fragments had masses equal to or greater than 4. The theoretical efficiencies for channels containing hydrogen isotopes, however, were too small because the protons were predicted to have broader angular distributions than observed.

The deduced cross sections of the different channels for each of the three beams (^{16}O, ^{14}N and ^{12}C) on Au target are plotted in Fig. 1 as a function of the separation energy (Q_O) for that channel. The channels and their Q_O values are given in the table adjacent to the figure. The absolute normalization was established by comparison of the measured elastic scattering to the Rutherford cross-section and also by comparing the inclusive yields of heavy ions to those measured with a solid-state detector in an earlier experiment [11]. The two determinations were in good agreement; the systematic error on the absolute normalization was estimated to be ±20%.

The channels shown in Fig. 1 are distinguished experimentally only by their combination of atomic numbers. For example, the contributions of $^{12}B+^{3}He+p$ and $^{10}B+^{4}He+d$ are summed together, and are plotted against the most positive Q_O value, or -23.1 MeV. The detection of ^{8}Be poses an additional complication in that there is a 60% probability that the two ^{4}He nuclei from the decay of a ^{8}Be(g.s.) nucleus will hit the same detector. Such double hits were identified as Z=4 and were not distinguished from $^{7,9}Be$. Therefore, we have summed all events which differed only by two Z=2 or one Z=4 fragment (such as 4*He, 2*He+Be, and Be+Be) and plotted them versus the most positive Q_O value. These channels are indicated by an arrow in Fig. 1.



^{16}O Channels	Q_o (MeV)
C He	-7.2
N H	-12.1
He He He He	-14.4
C H H	-22.3
B He H	-23.1
B Li	-30.9
Li He He H	-31.8
He He He H H	-34.3
Li Li He	-35.3
B H H H	-42.9
Li Li H H	-49.1
Li He H H H	-51.6

^{14}N Channels	Q_o (MeV)
C H	-7.6
B He	-11.6
Li He He	-16.1
He He He H	-17.6
B H H	-25.1
Li Li H	-33.4
Li He H H	-34.9
He He H H H	-37.4

^{12}C Channels	Q_o (MeV)
He He He	-7.3
B H	-16.0
Li He H	-24.6
He He H H	-27.1
Li Li	-28.2
Li H H H	-44.5
He H H H H	-46.9

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Fig. 1. Cross section of the different channels plotted versus the most positive Q_O value of all isotopic combinations consistent with the elements making up that channel. The channels containing a combination of two helium nuclei or a Be nucleus have been summed and are indicated by an arrow. The open circles show the results of a statistical-decay calculation [12].

The logarithm of the cross section (Fig. 1) correlates approximately with the value of Q_o over a range of 3 to 4 orders of magnitude in yield. (The correlation with Q_o value is much stronger than any correlation with particle multiplicity.) Thus, the cross section can be characterized approximately by a slope parameter, E_o, which has values of 6.4, 5.5 and 6.0 MeV (±0.4) for ^{16}O, ^{14}N, and ^{12}C, respectively. This exponential dependence provides the justification for plotting the cross sections against the most positive Q_o value.

As a first step in the analysis of these data, we assume that the excitation energy spectrum of the primary projectile-like nucleus prior to its decay can be reconstructed from the positions and energies of each of the detected particles. The total relative kinetic energy of the fragments in the center of mass system of the primary projectile-like nucleus is given by $K_{tot} = \Sigma_i\ 1/2m_i\ (V_i - V_{pp})^2$ where Vi and Vpp are the laboratory velocities of a fragment (with mass m_i) and the center of mass system, respectively. The excitation energy of the primary projectile-like nucleus is $E^* = K_{tot} - Q_o$, where Q_o is the appropriate Q value for that channel. Residual excitation energies of bound fragments were neglected. A correction has been made for the different isotopic compositions of a given channel by estimating the yields of the individual isotopic combinations using the above slope parameter and a weighting factor based on $\exp(Q_o/E_o)$. An appropriate number of events were then offset by the more negative Q_o value associated with that isotopic combination. Fig. 2 shows the resulting primary excitation spectrum for ^{16}O.

A standard interpretation of projectile breakup consists of factoring the reaction into two independent stages - a fast excitation process followed by decay. The decay may be slow and involve a series of sequential, binary decays. Or the decay may be prompt, implying that the breakup of the projectile occurs while it is still in the vicinity of the target or that its dissociation into three or more fragments occurs more or less simultaneously regardless of location (multifragmentation). It is possible, within this standard interpretation, to analyze the second stage of the reaction by making use of the primary excitation spectrum reconstructed from experiment. We have calculated the yields of the different channels in this way by considering a series of binary splits, governed by

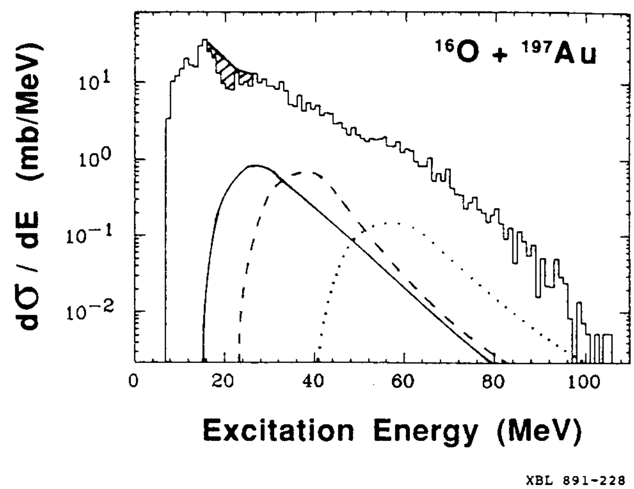

Fig.2. The spectrum of excitation energy of the primary projectile-like nucleus for the system $^{16}O + ^{197}Au$ target. The solid, dashed and dotted lines represent the contribution of the channels He+He+He+He,C+H+H and He+He+He+H+H respectively. The hatched area represents the estimated contribution of the undetected channel ^{15}O+n. The spectra for the other projectiles were qualitatively similar.

the density of states at the saddle point. Our calculation [12] is similar to one described by Auger, et al., [13] with the exception that we used ground state masses throughout and neglected rotational energy. An added feature of the present calculation is that, in any binary split, each of the fragments may undergo further decay.

The results of that calculation, in which the individual channels with the same combination of atomic numbers are summed to correspond to experiment, are shown in Fig. 1. In each case the input was the corresponding primary excitation spectrum (e.g., as in Fig. 2 for ^{16}O). The calculation compares favorably with experiment for Q_O values extending down to -30 MeV, which accounts for most of the cross section, but the yields at more negative Q_O values are poorly reproduced, with the calculated values being low by factors of five to twenty. We have also made similar calculations with LILITA (which includes angular momentum and the effects of discrete excited states, but considers the decay of the heavier object only) and obtained qualitatively similar results. Further comparisons of the predictions of a sequential decay model with experiment have been made by modelling the directional correlations of the emitted particles with LILITA. In this case also, general agreement was found for most of the cross section, but the predicted angular distribution of the protons was significantly broader than the experimental result.

The insensitivity of the detectors to free neutrons and the lack of mass resolution causes some ambiguity in interpreting the results. The contribution of the undetected channel, ^{15}O + n, was estimated by taking the shape of the excitation spectrum from that of N+H, normalizing the total yield according to the empirical dependence on Q_O, and shifting the spectrum by the difference in the Q_O and Coulomb barrier values. The estimated additional contribution of this channel is indicated by the dotted line in Fig. 2. Neutrons may also be picked up by the projectile. The pickup reaction $^{197}Au(^{16}O,^{17}O^*)$ has been studied recently by Gazes et al. and shown to populate the channels $^{13}C+^{4}He$ and $^{12}C+^{4}He+n$ [14]. Both of these channels are included in the experimental data for which $\Sigma Z=8$. Pickup reactions are also known to produce a generally higher excitation energy in the projectile-like nucleus than does inelastic scattering [15]. We have simulated this process and found that even a level of neutron pickup equal to the intensity of the inelastic scattering does not reproduce the experimental yields for channels with very negative Q_O values. Thus it appears that neutron pickup is at most a partial explanation for the events corresponding to high projectile excitation energies.

There are also reaction mechanisms that may contribute to projectile breakup but that do not strictly satisfy the assumption that all of the detected fragments result solely from the decay of the projectile. Pre-equilibrium emission of protons from the region of overlap between projectile and target is an example of this and might be responsible for the observed forward-peaked angular correlation of the protons relative to the expectation for sequential decay. Also, final state interactions between fragments of the projectile and the target can alter the directions of the fragments and thereby change the relative kinetic energy and deduced excitation energy [16]. Final state interactions do not affect that portion of the projectile excitation energy associated with the Q_O value for that channel, however.

In summary, the cross sections for the breakup of ^{16}O, ^{14}N and ^{12}C projectiles into a large number of different channels, some having as many as five charged particles, have been measured with an array of 34 plastic scintillators. This has enabled a more global examination of the breakup of the projectile than would be possible with two-particle coincidence experiments. The relative yields of the different channels were observed to correlate approximately with the threshold energy for separation of the projectile into the detected fragments. The excitation spectrum of the primary projectile-like nucleus, which was deduced from the separation energies and the measured positions and kinetic energies of the individual fragments, peaks at low excitation energies, but also extends to quite high excitation energies. A sequential decay model for the reaction mechanism can account for the bulk of the cross section and for the trends in the yields; nevertheless differences between this model and experiment do exist. These differences suggest that further examination of the standard assumption for projectile breakup is warranted and that comparison of present experimental results with other theories predicting the excitation and multiple dissociation of projectiles is desirable.

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